Design and Vibration Measurements of High Stiffness Massive Supports for the ESRF Nano-precision Engineering Platform Integration Laboratory

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Abstract

Within the framework of its nano-precision engineering platform, the ESRF has designed, built and commissioned two massive benches. These stiff support structures will serve for measurements of precise equipment in a controlled environment analogous to that encountered on ESRF beamlines.

The bases of the benches (1600x1000x540 mm) are made of concrete, for the first one, and in synthetic granite for the second. For each table, the top slab is made of natural granite (1600x1000x300 mm). The top slab and the massive support are connected together with precision leveller systems. Therefore, the top slab can be adjusted, in terms of height and tilt, on a geometry of three or four supporting points. A compressed spring, located underneath each leveller, increases its stiffness. In order to shift the natural frequency of the bench toward higher frequencies, six rigid stiffeners can be fixed on the side of the benches.

We have used the opportunity of building these two benches to answer various engineering questions. For this, vibration measurements were made in diverse mounting configurations. The paper will present the designs of the supports and will answer those questions, which are of prime interest for those who need to design such a structure. A vibration comparison study will be made between the cast concrete support block and the synthetic granite of the same geometry. Some elements of evaluation will be treated for the comparison between synthetic and natural granite, in terms of vibration behaviour. The efficiency of the stiffeners will be presented, as well as the effects of pre-loading the levellers. Finally, the variation of the system stiffness, with different numbers of support points, will be discussed.

1. Introduction

In view of the increasing number of Beamlines driven by nano-science projects and in order to prepare the upgrade program at the ESRF, a “Nano-Technology Platform” was set up in 2006 at the ESRF [1]. Within this platform various working groups have been created. One is the “Vibration Control Working Group”. It gathers a number of experts covering various fields of expertise, like mechanical engineering, Finite Element Analysis computation and vibration measurements. The missions of this working group are to investigate and to advise on the best strategies to minimise the effect of ground vibrations inherent at the ESRF site particularly with respect to the challenges associated with nanometre sized beams.

The 50 m^2 area Integration Laboratory of the ESRF is now a place where many of the sensitive ESRF instruments will be assembled and tested. Its environment is close to the typical conditions of an ESRF beamline. In particular, the vibration level is kept as low as possible, the temperature is closely controlled (i.e. 0.15º C peak to peak over more than a week), as well as its cleanliness (i.e. class 10000 clean room).

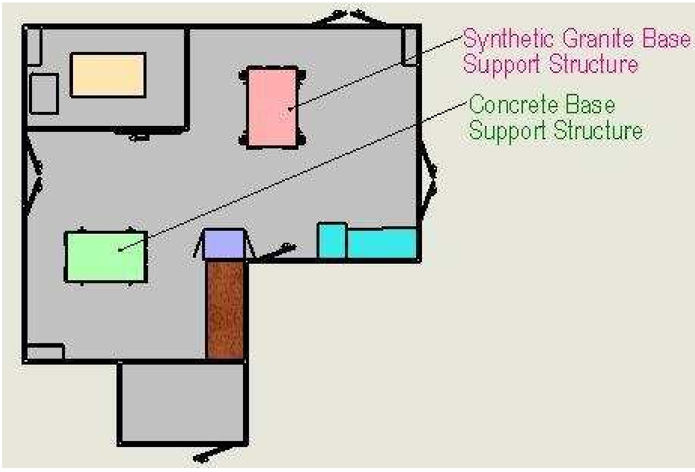


Figure 1. Integration Laboratory layout

In order to test different solutions, we have identified the need for two stiff support structures (work benches), which serve as stable experiment tables (see Figure 1). The benches must exhibit the following characteristics:

- Very good flatness of the top surface
- Thermal stability (large inertia, low thermal expansion coefficient)
- Bending and torsion vibration modes at high frequencies (i.e. >> 100Hz)
- Static stability (i.e. no deformation when loaded)

All these reasons led to the choice of massive and rigid benches. This preserves the high stiffness to mass ratio necessary to obtain high resonance frequencies for the structures.

The design, construction and commissioning of those two working benches fell under the responsibility of the "Vibration Control Working Group". Vibration measurements were performed at the different stages of the construction and will be presented in this paper.

For many years, the ESRF mechanical engineering group has been designing both light [2] and massive instrument support benches with particular attention paid to minimising the vibration response of the engineered structures. The building of the two benches in the Integration Laboratory was an ideal occasion to gather and compare all of the experience accumulated in this domain and to characterise, in a same location and in the same conditions, different designs.

Here is a list of questions that the vibration measurements on the two benches must help to answer. Those answers will be of prime interest for the forthcoming massive benches that will be constructed for the ESRF beamlines in relation to the ESRF upgrade program [3].

- Is the concrete block as stiff as the synthetic granite block?
- For tilt and height adjustments of the top slab, are 3 feet sufficient or do we need 4 or more, as far as rigidity is concerned?
- Do we need to add an extra loading on the levelling supports (by means of a compressed spring) in order to increase the rigidity of the contact?
- To increase the vertical adjustment stroke of the table, could we reasonably put additional levellers between the floor and the synthetic granite block and therefore do we need extra reinforcement (corner stiffeners) to compensate the loss of rigidity induced by this supplementary interface?
- Is it useful to include rib stiffeners between the base block and the top granite slab in order to shift the natural frequency of the system towards higher values?

2. Concrete base support structure

For the first bench, it was decided to pour in-situ a large block of concrete serving as the base block of the bench (Figure 2). Five levelling systems (Figure 3), based on Airloc 2140-KSKC, have been fixed on top of the concrete block. This configuration, with five independent levelling systems, allows the user to support the granite slab either on 3, 4 or even 5 support points. This type of Airloc has a full vertical stroke of 13 mm.

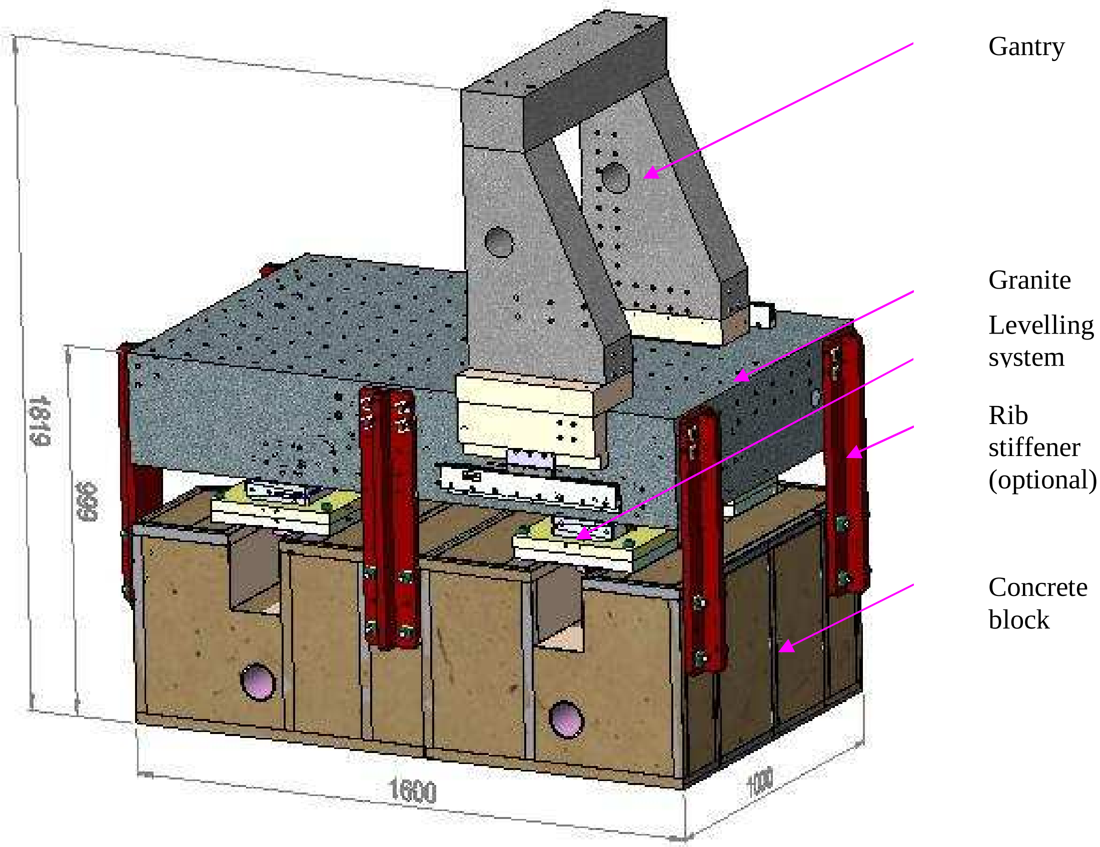


Figure 2. View of the concrete based working bench (with the Airloc set at their median position)

In order to have the five Airloc resting on the same horizontal plane, 5 aluminium plates (see Figure 3) have been levelled and then bolted to the concrete top surface. A mortar layer (type *CLAVEXPRESS 700* from Parexlanko) was poured between the concrete and the aluminium plate increasing the rigidity of the mounting (see §2.3.1 for the vibration measurements). This mortar exhibits no shrinkage upon setting and hardening.

The spring, located underneath of the Airloc, allows a supplementary pre-load to be applied the Airloc leveller in order to increase its stiffness. Indeed, the weight of the granite table is 1.48 ton, which might not be sufficient in order to get the best stiffness out of the levelling system. Therefore, up to one ton can be added, on each Airloc, by compressing the loading spring.

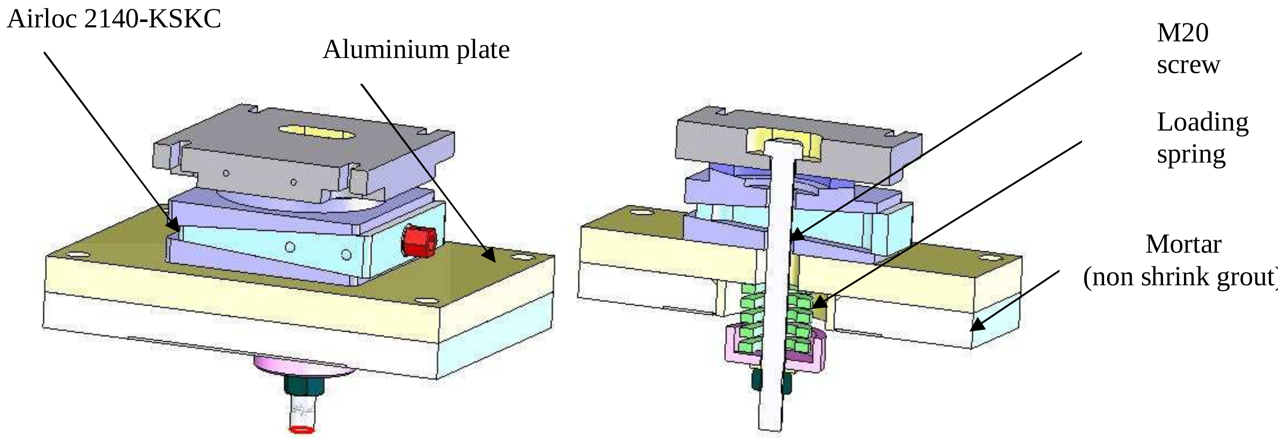


Figure 3. Full and half views of the levelling system

2.1. Construction of the concrete block

In order to ensure optimum adherence between the cast concrete block and the floor, the preparation work consisted of hammering the top layer of the concrete floor. The welded angle-iron frame was then fixed to the floor. Installation of the steel reinforcement bar framework was performed on site (Figure 4).

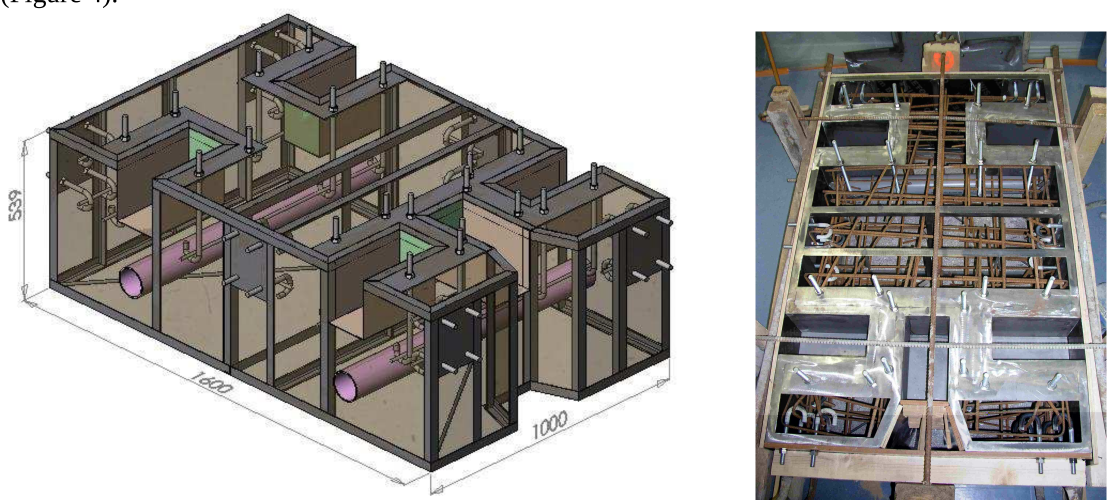


Figure 4. Block structure model and picture of the iron framework made before pouring concrete

As shown on Figure 5, the concrete was cast on site (in the clean room) using 250 litre buckets. This part of the work was delicate due to the cleanliness of the room. After the construction of the block, the room was entirely cleaned.

In order to be able to reproduce exactly such a concrete block for future projects, a full series of tests took place during and after the pouring; for characterisation of the concrete.

The concrete composition is presented in Table 1. With this type of formulation, the goal was to obtain a concrete that has a minimum withdrawal during drying and should attain, after 28 days, a nominal compressive strength of 30 MPa.

Table 1. Concrete composition for 1 m^3

	Type	Weight [kg]
Cement	CEM II 42.5 N CP2	350
Sand	0/4R	810
Gravel	4/12	380
Gravel	12/20	760
Adjuvant	Structuro 311 (FOSROC)	0.60 %
Water		140

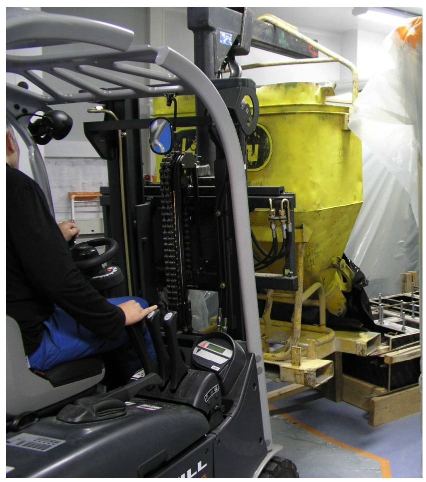


Figure 5. Pouring of the concrete in the clean room

The following measurements were made on the concrete sample:

- Shrinkage curves made on 7x7x28 cm samples and measured at 1,7,14 and 28 days after pouring. A withdrawal of 190 µm/m was measured after 28 days.
- Compression strength measurements on cylindrical samples (Ø16x32 cm) after 2,7,14 and 28 days. A compressive strength of 39 MPa was measured after 28 days.
- Settling measurement of the fresh concrete. The *slump test*, made with an Abrams cone, reveals a settling of 105 mm once the cone was overturned. The slump is the distance that the centre of the cone top settles. A slump of less than 25 mm indicates a ‘thick’ concrete and a slump of more than 125 mm indicates a very fluid concrete.
- Density measurements of the concrete at different stages of the drying after 7, 14 and 28 days (see Table 2 for results).

Table 2. Evolution of the concrete density

Numbers of days	Concrete density [kg/m^3]	Concrete density variation [%]
0	2515.6	
7	2454.6	2.42
14	2448.7	2.66
28	2443.6	2.86

2.2. Gantry

As shown on Figure 2, a 250 kg gantry made of granite was installed on the top of the granite table. An ironless linear motor (ref: ETEL ILF06-030) was fixed on the side of the granite slab to actuate the gantry. For this movement, air-bearings based on a combination of compressed air and vacuum pads is used. The “Linear Stage Working Group” of the “Nano-Precision Engineering Platform” made this design in order to master the pads combination technology as well as the linear motor. Once the gantry is fully characterised, the gantry will be used as a tool for precise measurements. Detailed study of the gantry behaviour will form the basis of a future publication.

2.3. Vibration measurement results of the bench (made without rib stiffeners)

In order to characterise the behaviour of the support structure, various vibration measurements were made. For that purpose, L4-C geophones from SERCEL were interfaced with an OROS OR36 spectrum analyser. The useful bandwidth of the recorded data is in the range 1 to 100Hz. In all cases, the response of the structure was measured without additional excitation. A reference sensor on the floor was used throughout. The frequency results are expressed as displacement Power Spectral Density (unit: $\mu m^2/Hz$) in order to normalise with respect to time windowing. Note that the square root of the integral of the displacement PSD over frequency leads to rms displacement [4].

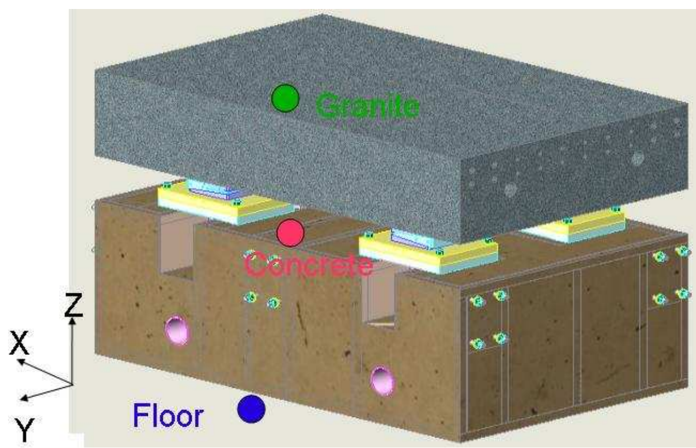
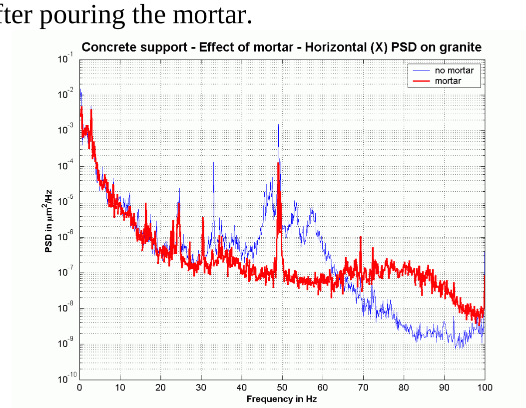


Figure 6. Concrete base support structure and position of the geophones

2.3.1 Effects of the mortar between the Airloc base support plate and of the concrete

As presented previously (see Figure 3) a specific mortar was poured between the top of the concrete block and the Airloc’ base plates (made of aluminium). The vibration measurements presented in Figure 7, were made before and after pouring the mortar.



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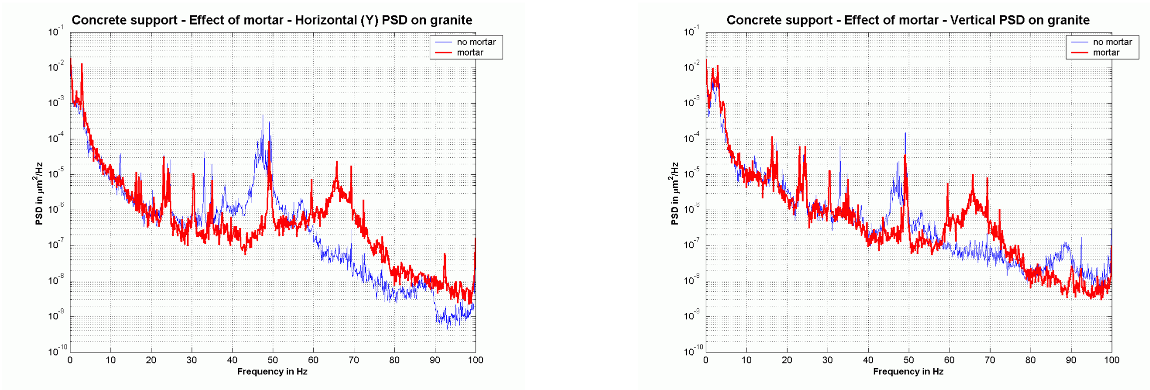


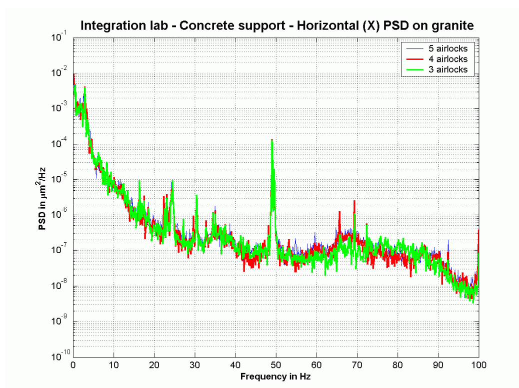
(b) (c)

Figure 7. Vibration measurements (Power Spectral Density vs frequency) made before and after pouring the mortar. The 3 geophones have been put on top of the granite slab.

By adding this mortar, Figure 7 shows clearly a drastic shift of the natural frequency of the support structure by 35, 19 and 16 Hz respectively along the X, Y and Z directions and towards the higher frequency. Therefore this mortar layer significantly improves the rigidity of the support structure.

2.3.2 Effects of the number of Airloc

By having installed five independent levellers, we can choose to rest the top slab either on 3 or 4 or even 5 support points. Figure 8 shows the measurements for all of those configurations and for the 3 components.



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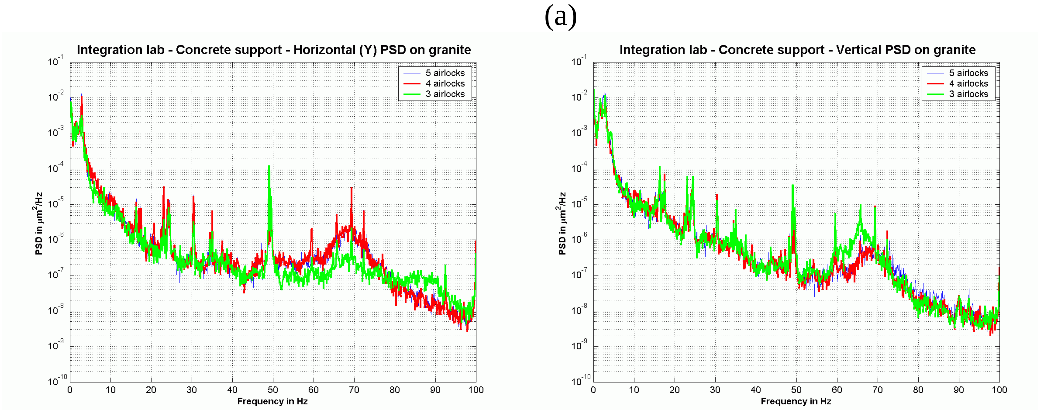


(b) (c)

Figure 8. Vibration measurements made with 3-4-5 support points. Response obtained on top of the granite slab.

The variation of stiffness is rather small when we support the load in 3 or 4 or even 5 points. In the best case we can only shift the natural frequency by 4 to 5 Hz (in the Y and Z directions) and reduce slightly the PSD (by 7 10^{-6} μm^2/Hz along the Z axis). As far as dynamic stiffness is concerned, a 3-point support structure seems sufficient. Figure 9 shows the vibration measurement of the support structure (along Y axis) when fitted with 3 Airlocs. For this measurement, the geophone responses were taken at different positions along the vertical axis (as shown in Figure 6)

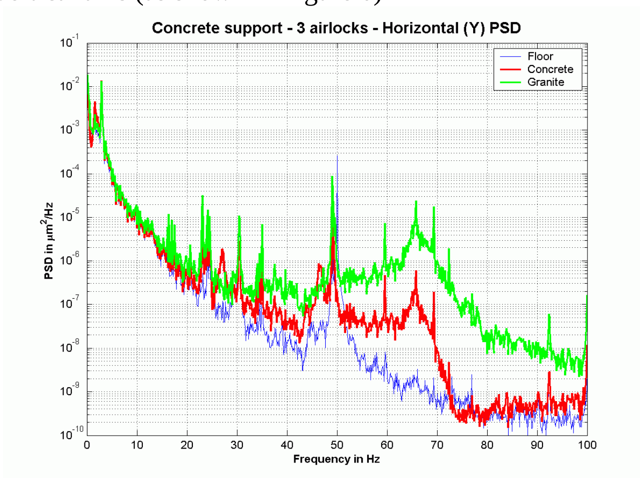


Figure 9. Vibration measurements (along Y axis) made with a 3-Airloc configuration. Response obtained on the floor, on the top of the concrete structure and on top of the granite slab.

On Figure 9, we can clearly see that there is a strong excitation peak at 49 Hz for the three components. According to some other vibration measurements, this excitation may correspond to some electrical pumps located close to the Integration Laboratory. After full investigation, actions will be taken to reduce the vibration induced by such pump(s).

2.3.3 Effects of adding a gantry on the granite slab

After adding the gantry, and its linear motorization, an additional set of measurements was made to see the influence of adding a mass on top of the granite slab (see Figure 10). For those measurements, only 3 Airloc systems were used to support the load.

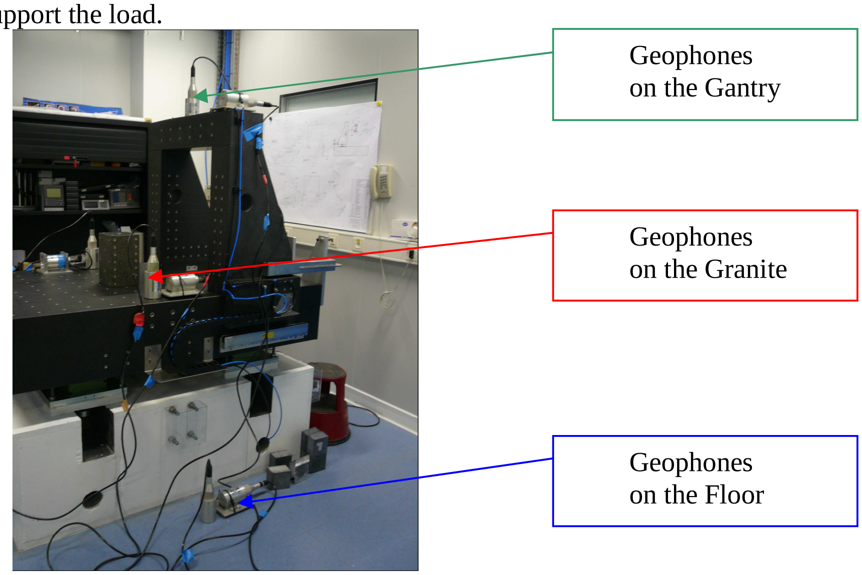
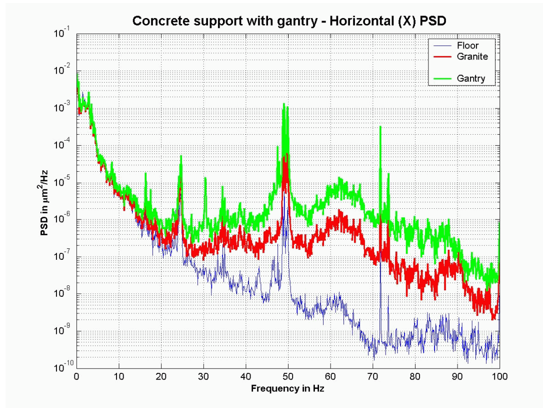


Figure 10. Picture of the bench and its gantry fitted with the measurement setup

Figure11 shows the vibration measurements obtained by putting the geophones at different locations on the setup.



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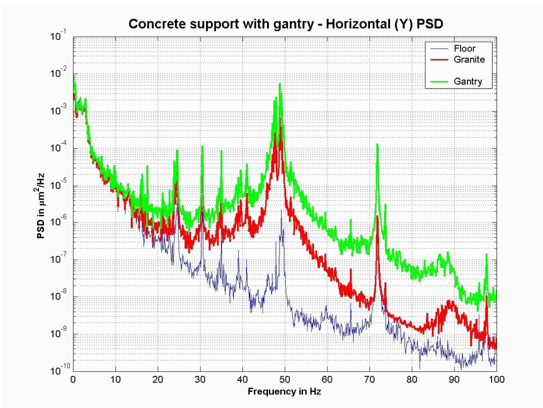

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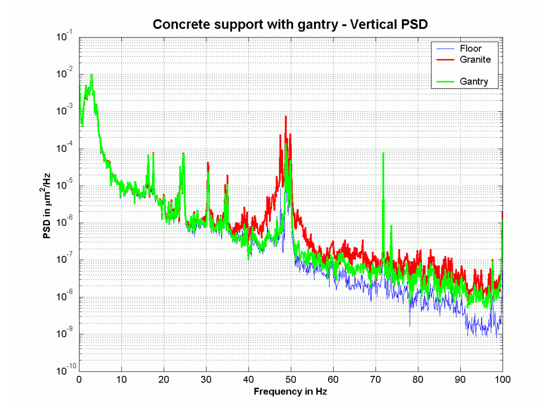


(c)

Figure 11. Vibration measurements along the 3 axis and at different locations.

The above curves should be compared with the ones of Figure 7 (after pouring the mortar). By doing so we can see that the additional load, induced by the installation of the gantry, has shifted significantly the natural frequency towards the lower frequencies as shown in Table 3.

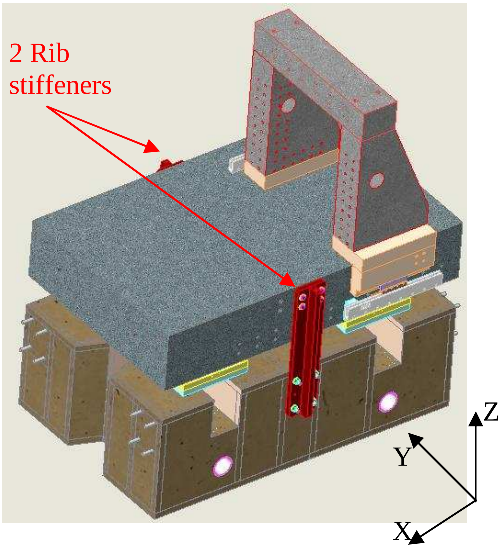
Table 3. Comparison of the natural frequency before and after the gantry installation

Along axis	Natural frequency [Hz] without the gantry (Fig. 7)	Natural frequency [Hz] with the gantry (Fig. 11; curve=granite)
X	83	63
Y	66	47
Z	64	48

Adding a supplementary mass, furthermore with a high centre of gravity, led to a significant reduction in natural frequency and an increase of the vibration amplitude. This amplitude increases with height.

2.3.4 Effects of adding rib stiffeners on two sides (longer sides)

In order to increase the stiffness of the structure (absolutely necessary due to the detrimental effect of the gantry installation), two rib stiffeners were installed on the longer sides. Provisions were made during the design stage to accommodate a total of 6 rib stiffeners around the perimeter of the granite slab. Figure 12 shows the picture of the system as well as the vibration measurement results along the Y axis.



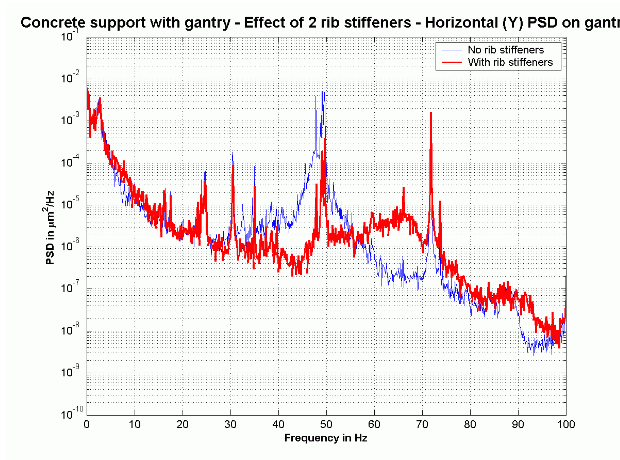


Figure 12. Picture of the system and vibration measurement (along Y axis) without and with 2 rib stiffeners

It is obvious that such stiffeners have considerable capacity to shift the natural frequency toward higher values (i.e. 65 Hz instead of 47 Hz). The vibration amplitude has also been reduced significantly. Measurements along X and Z do not reveal any frequency shift.

2.4 Future prospects

This bench is now validated to measure instruments installed on the top granite slab. It is rigid enough and only 3 support points are necessary. However, according to the measurements, when the gantry is put in place it might be necessary to increase the stiffness of this bench. Therefore it is planned to:

- repeat the vibration measurements by adding 4 more corner stiffeners (2 on each shorter sides of the granite) in order to increase the rigidity also along X and Z
- measure the effect of 3, 4 and 5 support points
- characterise the pre-loading of the springs

3 Synthetic granite base support structure

3.1. Assembly description

The second bench, delivered to the ESRF Integration Laboratory, has a base made of synthetic granite (*CELITH* type, manufactured by MICROPLAN). This material (see Table 4 for characteristics) is obtained by mixing an epoxy resin to different sizes of granite pebbles (*Diorite*, which has fine diameter, and *Blue granite from Guéret* which has bigger size grading). The final block is obtained by casting this mixture in to a mould, which has the final dimensions of the block. The surface of the block in contact with the levellers is ground with classical machining tools. With this casting technique, complex shapes can be obtained. In addition, the resulting block is known to have relatively good vibration damping characteristics.

Table 4. Mechanical and thermal properties of the natural and synthetic granite [5]

	Natural granite	CELITH granite
Density [kg/dm3]	2.7-3	2.3-2.5
Elasticity modulus [kN/mm²]	35-45	30-40
Linear thermal expansion coef. [10^{-6}/°C]	5-7	9-13
Thermal conductibility [W/m.°C]	2	1-3
Compressive strength [N/mm²]	350	120-150
Tensile strength [N/mm²]	10-15	10-15

As shown in Figure 13, the synthetic granite block laid on 4 Airloc; used for height and tilt adjustment purpose. After this adjustment, each Airloc is bolted rigidly to the floor with two M20 threaded rods (as shown in Figure 14). In addition, four corner stiffeners could be bolted to increase the stiffness of the support (see §3.2.1). The top natural granite slab is fixed to 5 motorised Airloc systems, bolted to the synthetic granite block. If necessary, 6 rib stiffeners might be used to enhance the links between the synthetic granite and the granite block.

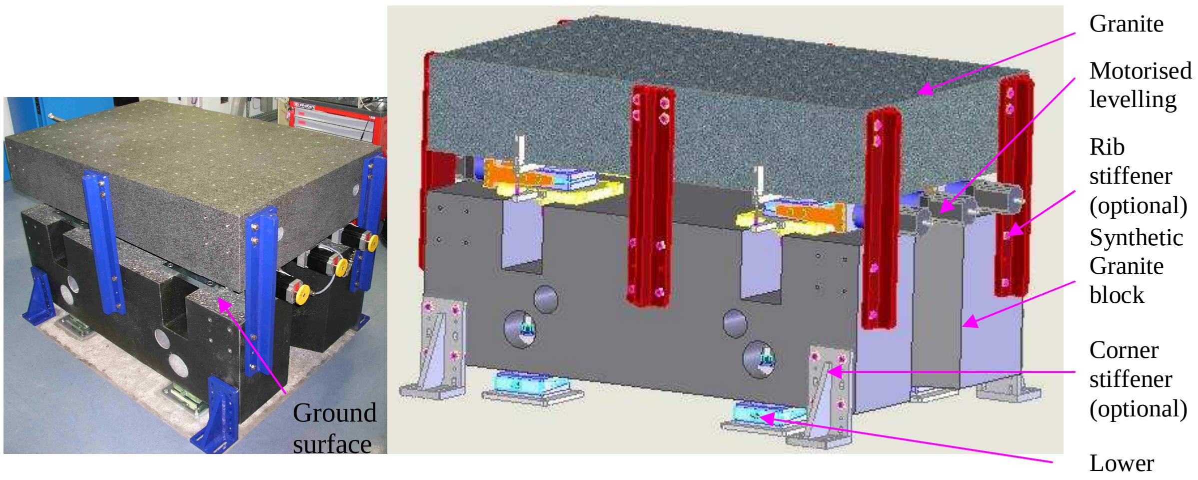


Figure 13. Picture and model of the synthetic granite based bench (1600x100x1061 height)

The levelling system, located between the 2 blocks, is similar to the one of the first bench (described in § 2) but this one is independently motorised (see Figure 15) and has a comparator fixed on it for metrology purposes. Figure 14 shows the levelling system layout as well as some details of the lower layer of Airloc supports. As for the first bench, the operator can choose to support the top slab on 3 to 5 points.

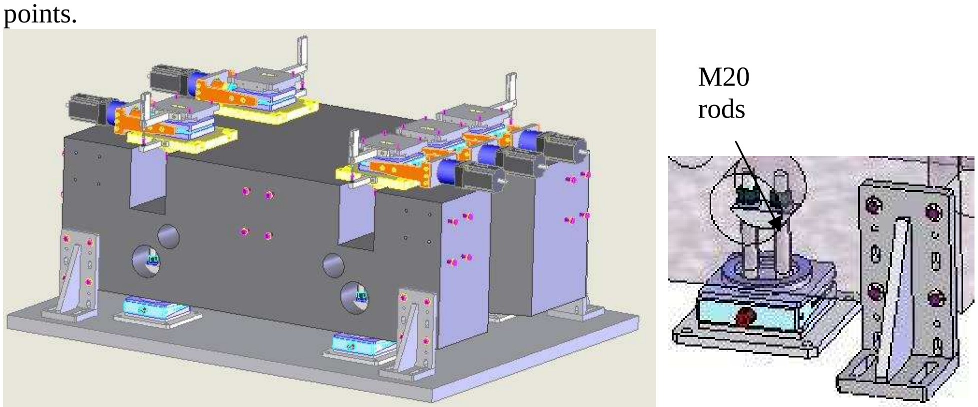


Figure 14. Lower part of the bench and detail of the lower Airloc layer

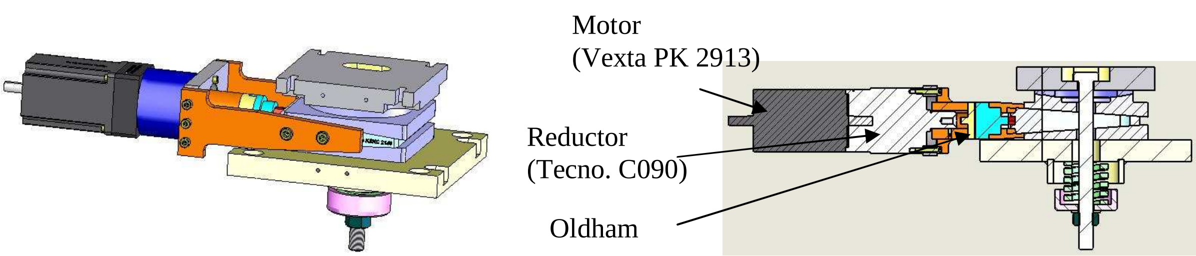


Figure 15. Motorised Airloc levellers (full and half view)

3.2. Vibration measurement results of the bench

As for the concrete base support, a full set of vibration measurements was made to characterize the bench and its equipment. Figure 16 shows the positions of the geophones as well as their measurement response along the horizontal axis, Y. Those curves are to be compared with the curves of Figure 9, corresponding to the first support structure (without the gantry and supported on 3 Airloc). By comparing those curves, we can clearly see that the natural frequency is now reduced from 66 to 40 Hz.

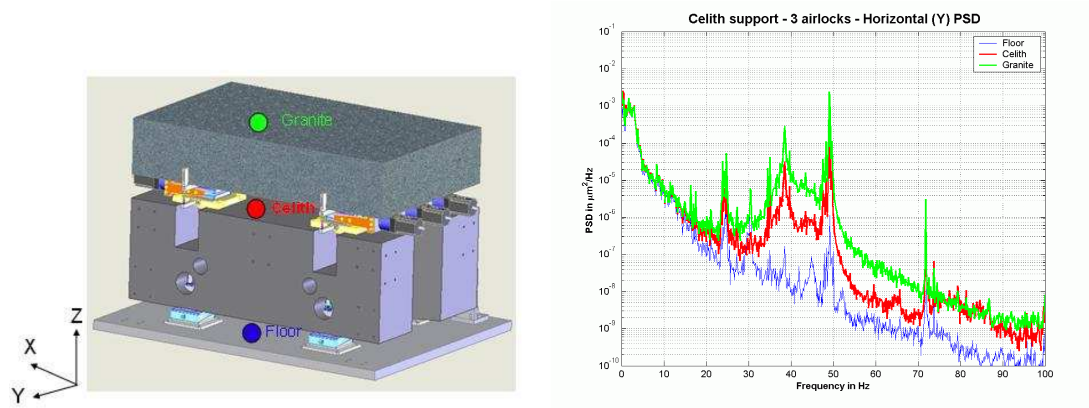


Figure 16. Position of the geophones and vibration measurements along the Y- axis at the different height.

3.2.1. Effects of adding 4 corner stiffeners

The above structure exhibits clearly a lack of rigidity. To improve this, four corner stiffeners have been bolted rigidly between the floor and the vertical surfaces of the synthetic granite block. Figure 17 shows the characterization of the corner plates. Along the X direction, the natural frequency has shifted from 39 to 52 Hz, and from 39 to 49 Hz along the Y direction. The effect of the corner stiffeners is therefore not negligible and such reinforcements will be kept in place to increase the rigidity of the base block.

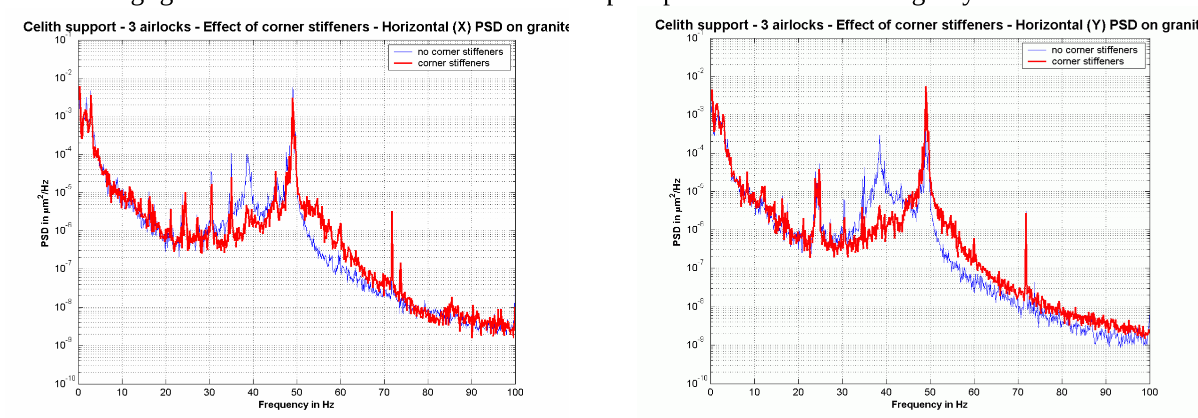


Figure 17.Vibration measurements on top of the granite top slab (along X and Y directions) to characterise the corner stiffeners

3.2.2. Effects of spring pre-loading

By keeping in place the corner stiffeners, and resting on 3 support points, another set of measurements took place to measure the effect of the preloading of the springs located underneath of the second stage of Airloc (as shown in Figure 15). Results are presented in Figure 18.

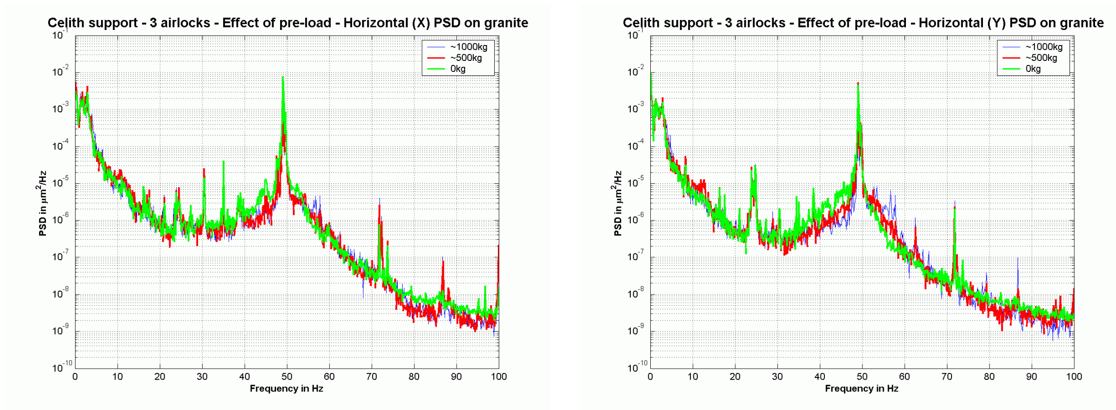


Figure 18. Pre-loading effect of the springs. Measurements made on the top of the natural granite slab, along X and Y directions

Surprisingly, no major change was measured when the spring was loaded up to 1000 kg. This might be due to the weak rigidity at the floor interface (apparently, the extra rigidity achieved with the corner stiffeners is not sufficient). A modification of one parameter, located above the synthetic granite block, can only produce minor effects due to the lack of rigidity of the link between the floor and the base block. PSD in the horizontal directions are presented for 3 different pre-loads. The same types of results have been obtained by trying to characterise the rib stiffeners; nearly no variation of the frequency spectrum was noticeable due to the lack of rigidity of the base part link.

3.3 Future prospects

Presently, and due to the lack of rigidity of the link between the floor and the block, the synthetic granite based support structure was dismantled in order to remove the lower Airloc adjustment levellers. An epoxy resin (which is not yet selected) will be injected underneath of the synthetic granite block. The corner stiffeners will serve to position the synthetic granite (at a height of 5 mm) during the resin injection process (see Figure 19). After the resin hardening, the feet will be removed definitively and vibration measurements will be repeated. Pre-loading and rib stiffeners characterisation will be repeated after this modification.

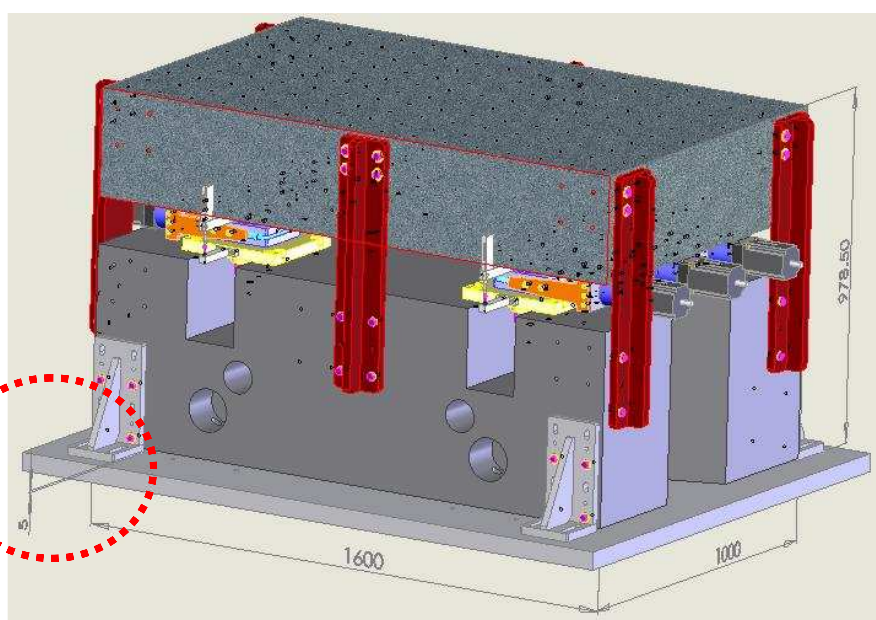


Figure 19. Synthetic granite positioned vertically at 5 mm from the floor

After the full characterisation of the bench and its motorised Airloc, it is planned to dismantle the top part of the bench to replace the Airloc by Nivell levellers. The latter are known to be stiffer but their stroke is more limited (10 mm rather than 13 mm for the Airloc).

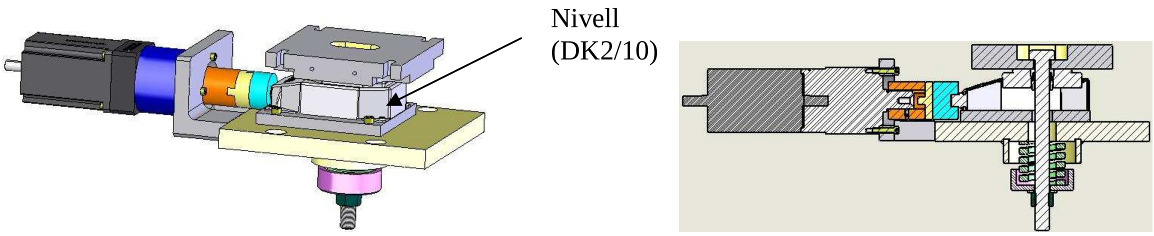


Figure 20. Motorised Nivell levellers (full and half view)

4 Conclusions

After having designed, built and characterised the two support structures, it was concluded that:

- Poured concrete support is more rigid and stable than synthetic granite support in the current configuration. This is essentially due to the better bonding of the poured-concrete base support to the floor than the Airloc bonding of the synthetic granite base support to the floor. Gluing the synthetic granite base directly to the floor should significantly improve stability of the whole support table.
- Additional masses, in particular with high centre of gravity such as gantries, affect the response of the supports, reducing the resonant frequencies.
- 3 Airloc under top granite slab seem to be sufficient as far as rigidity is concerned and for an experiment taking place on the top of the slab (probably 3 contact points are not enough for a gantry experiment).
- The effects of the rib stiffeners for the two support structures are different:
  - the rib stiffeners for the concrete base support structure improve stiffness of the link between the top granite slab and the concrete base giving a consequent reduction of the gantry excitation.
  - the rib stiffeners for the synthetic granite base support structure presently have a very limited effect. For this support structure, the weak point is the Airloc link between the synthetic granite and the floor.
- The corner stiffeners, installed to reinforce the link between the synthetic granite and the floor, have a significant effect on the rigidity, but this is not enough to compensate the loss of rigidity induced by the first layer of Airloc.

5 Acknowledgements

The authors gratefully acknowledge the ESRF staffs who have contributed to the design and the building of the two support structures. Among those people we would like to thank the Draughtsmen (Jean-Francois Ribois and Eric Gagliardini), Claude Richard (of the Mounting and Adjusting group), the Handling Group (Ceferino Alonso and his team) and the Survey and Alignment Group (Noel Levet and his team).

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